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**CALCULATED DYNAMIC CHARACTERISTICS OF A SOFT-INPLANE
HINGELESS ROTOR HELICOPTER**

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NOMENCLATURE

c	rotor blade chord
C_T	rotor thrust coefficient (thrust divided by $\rho \pi R^2 (\Omega R)^2$)
$(L_{HT}/q)_{HT}$	horizontal tail lift-curve slope divided by dynamic pressure
R	rotor radius
$t_{\frac{1}{2}}$	time to half-amplitude (time to double-amplitude when negative)
T	period
V	helicopter forward speed
x_A	blade chordwise aerodynamic center position, positive aft of the pitch axis
x_I	blade chordwise center of gravity position, positive aft of the pitch axis
β_0	main rotor trim elastic coning angle
β_{lc}	main rotor trim longitudinal tip-path plane tilt angle
β_{ls}	main rotor trim lateral tip-path plane tilt angle
δ	rotor blade Lock number
ζ	damping ratio of an eigenvalue
ζ_0	main rotor trim collective lag angle
Θ_{FT}	helicopter trim pitch angle
Θ_{tr}	tail rotor collective pitch angle
Θ_{lc}	main rotor lateral cyclic pitch angle
Θ_{ls}	main rotor longitudinal cyclic pitch angle
Θ_{75}	main rotor collective pitch angle at 75% radius
μ	rotor advance ratio (helicopter forward speed divided by rotor tip speed)
γ_β	blade rotating flap natural frequency
γ_ζ	blade rotating lag natural frequency
ρ	air density
σ	rotor solidity ratio (blade area divided by disk area)
Φ_{FT}	helicopter trim roll angle
ω_{θ_0}	blade rigid pitch natural frequency
ω_{θ_1}	blade elastic torsion natural frequency
Ω	rotor rotational speed

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SUMMARY

Calculated dynamic characteristics of a representative soft-inplane hingeless rotor helicopter are presented. The flight dynamics as a function of speed and gross weight are given. The requirements for accurate analytical modelling of this helicopter are established. The influence of the horizontal tail size, the rotor precone, the blade sweep, and the blade center of gravity/aerodynamic center offset on the calculated flight dynamics and aeroelastic stability are examined. The calculations show no evidence of an air resonance stability problem with this aircraft.

INTRODUCTION

The BO-105 helicopter is a production aircraft utilizing a soft-inplane hingeless main rotor. A hingeless rotor has a major influence on the dynamic characteristics of a helicopter, including the flight dynamics and aeroelastic stability. Also, with a soft-inplane rotor the possibility of an air resonance instability is introduced. This report presents the results of a theoretical investigation of the BO-105 helicopter dynamics. The investigation includes calculations of the flight dynamics and air resonance behavior; consideration of the analytical modelling requirements; and an examination of the influence of the rotor parameters. The purpose of this work is first to investigate the dynamic characteristics of this representative hingeless rotor helicopter, in particular the influence of rotor parameters on the flight dynamics and aeroelastic stability; and secondly to demonstrate the applicability of the rotorcraft aeroelastic analysis developed in reference 1 to hingeless rotor helicopters.

The analysis on which these calculations were based is described in reference 1. The input data describing the BO-105 helicopter were obtained from references 2 and 3.

DESCRIPTION OF THE HELICOPTER

The BO-105 helicopter has a four-bladed hingeless rotor of radius $R = 4.9$ m, operated at a tip speed of $\Omega R = 218$ m/sec. The rotor has a solidity ratio of $\sigma = 0.07$, and the blade Lock number is $\gamma = 5.0$. The calculated natural frequencies of the rotating blade are $\omega_{\beta} = 1.12/\text{rev}$ for the fundamental flap mode, and $\omega_{\xi} = 0.74/\text{rev}$ for the fundamental lag mode. The blade elastic torsion mode has a natural frequency $\omega_{\theta} = 3.66/\text{rev}$. No information was available about the control system stiffness, so it was assumed that the blade rigid pitch motion has a natural frequency of $\omega_{\theta_0} = 5.8/\text{rev}$ for the collective mode, $5.3/\text{rev}$ for the cyclic modes, and $6.5/\text{rev}$ for the reactionless mode (giving a coupled rigid pitch/elastic torsion natural frequency of about $3.4/\text{rev}$).

The rotor hub has 2.5° of built-in precone, and no built-in droop or sweep of the blade outboard of the pitch bearing. It is assumed that the hub is rigid with no bending deflection at the pitch bearing, and so there is no kinematic pitch/bending coupling. The blade section aerodynamic center and center of gravity have no chordwise offset from the pitch axis. A structural damping level of 3% critical was used for the blade bending and torsion motions.

The analysis included the following degrees of freedom: two bending modes (fundamental flap and lag), rigid pitch, and elastic torsion for each blade; the six rigid body motions of the helicopter; tail rotor flapping; and inflow perturbations for the tail rotor and main rotor. The inflow and tail rotor degrees of freedom were quasistatic (see reference 1). The rotor was assumed to be operating at constant rotational speed. Stall and compressibility effects were included in the rotor aerodynamics. Rotor/tail and rotor/rotor aerodynamic interference effects were not considered. The

constant coefficient approximation was used to evaluate the dynamic characteristics in forward flight.

The dynamic characteristics were calculated for the helicopter in level flight at forward speeds from $V = 0$ to 120 knots, corresponding to an advance ratio of $\mu = 0$ to 0.28. The basic operating condition considered is a gross weight of 1800 kg, corresponding to a thrust coefficient to solidity ratio of $C_T/\sigma = 0.0575$; sea level, standard day; out of ground effect; and mid center of gravity position.

HELICOPTER TRIM

Figures 1 to 4 present the calculated BC-105 trim for a gross weight of 1800 kg, at forward speeds from hover to 120 knots. The control position and fuselage attitude given in figures 1 and 2 generally agree with the calculations and experimental results of reference 4 (figures 10 and 11), except of course for the lateral cyclic control Θ_{lc} (the analysis considered only a uniform induced velocity). The information about the flight conditions of the test results in reference 4 is not sufficient to attempt a detailed correlation with the present calculations. Figure 3 gives the calculated power required of the helicopter, and figure 4 gives the trim flap and lag motion of the rotor. The collective lag angle ξ_0 varies as the rotor power. The cyclic flapping angles (longitudinal and lateral tip-path plane tilt, β_{lc} and β_{ls}) are small because the helicopter center of gravity is near the rotor shaft axis for the case considered. There is a small amount of negative elastic coning of the rotor because the hub preconing of 2.5° is ideal for a slightly higher gross weight than the 1800 kg considered here.

FLIGHT DYNAMICS

Figures 5 to 7 present the calculated flight dynamics of the BC-105 helicopter as a function of speed and gross weight. The hover longitudinal oscillation is only moderately unstable (figure 5), because of the high pitch damping of the hingeless rotor. At high speeds the time to double-amplitude of the longitudinal oscillation decreases due to the rotor

angle-of-attack instability. The trends of the calculated period and time to double-amplitude of the longitudinal mode are confirmed by the theory and experimental results of reference 4 (figure 13), although again the information about the test flight conditions is not sufficient for detailed correlations. The lateral oscillation becomes a highly-damped short period mode due to the large directional stability contribution of the tail rotor. The yaw/spiral mode time constant is large in forward flight (figure 6), indicating that as desired the response to lateral cyclic is a roll rate rather than a roll attitude change. Separate pitch and roll roots can be identified (figure 6), but both of these modes actually involve coupled pitch and roll motion. The pitch and roll modes are also highly coupled with the low frequency flap mode (an oscillation with a time to half-amplitude of $t_{\frac{1}{2}} = 0.06$ to 0.07 sec). The low frequency lag mode has a time to half-amplitude of $t_{\frac{1}{2}} = 0.5$ to 0.8 sec. The principal effect of increasing gross weight shown in figure 7 is a decrease in the time to double-amplitude of the longitudinal oscillatory mode in forward flight.

ANALYTICAL MODELLING REQUIREMENTS

Consider now what elements of the analytical model are required to accurately represent the dynamics of this hingeless rotor helicopter. Figure 8 shows the influence on the oscillatory modes of a decoupled rigid body dynamic model, or a quasistatic rotor model. In the decoupled dynamics model only three rigid body degrees of freedom are included: longitudinal velocity, vertical velocity, and pitch for the longitudinal dynamics; or lateral velocity, roll, and yaw for the lateral dynamics. The implementation of the quasistatic rotor model, for which the rotor influence is reduced to simply stability derivatives, is discussed in reference 1. The vertical and yaw modes (not shown) are not affected much by either of these modelling changes. The pitch and roll modes are higher frequency and involve coupled longitudinal/lateral motion, hence are more sensitive to these changes. Generally the uncoupled dynamics and quasistatic rotor approximations are acceptable if a low order model is required for the flight dynamics.

Figure 9 shows the effect on the calculated flight dynamics of successively dropping from the analytical model the rotor inflow perturbation, the blade torsion motion, and the blade lag motion. For this hingeless rotor helicopter all of these degrees of freedom are required in order to adequately model the flight dynamics.

AIR RESONANCE

Figure 10 shows the damping ratio of the low frequency lag mode as a function of forward speed, including the influence of the analytical model. The blade torsion dynamics are important to the helicopter air resonance behavior, but the influence is primarily a quasistatic pitch/bending coupling. The theory and experimental results in reference 5 (figure 22) show a similar insensitivity of the air resonance stability to speed.

The calculations showed no evidence of air resonance problems with this helicopter. For some values of the rotor parameters (precone, sweep, or droop) there can be a blade lag instability, which is not the same as an air resonance instability. The former involves all the lag modes of the rotor, while the latter involves only the low frequency lag mode. Also, air resonance is potentially more destructive since the low frequency lag mode produces a whirling motion of the rotor center of gravity about the shaft.

HORIZONTAL TAIL INFLUENCE

Figure 11 shows the calculated influence of increased horizontal tail effectiveness on the longitudinal oscillatory mode. A mildly stable long period longitudinal oscillation (not shown in figure 11 because the time to half-amplitude is very large) is produced above about 70 knots with $(L_{\alpha}/q)_{HT} = 9 \text{ m}^2$ (three times the baseline tail size). Increased tail effectiveness also produces a short period oscillation from the vertical and pitch roots above about 40 knots, with a period of $T = 2$ to 3 sec, and a time to half-amplitude of around $t_{\frac{1}{2}} = 0.2$ sec at high speed. The calculated results of reference 4 (figure 16) agree with these

trends. However, aerodynamic interference, which has not been included in the present model, would tend to reduce the tail efficiency at low and moderate forward speeds by stalling the tail and lowering the dynamic pressure.

INFLUENCE OF ROTOR PARAMETERS

Figures 12 to 16 present the influence of possible changes in the rotor precone, sweep, center of gravity offset, and aerodynamic center offset on the calculated flight dynamics. A precone increase (figure 12) degrades the hover longitudinal oscillation, but improves the lateral oscillation and the forward flight longitudinal oscillation. A lag instability is predicted at a precone angle of about 3.5° for this gross weight; the combination of high precone and low gross weight produces large negative trim elastic coning of the blade, hence unfavorable pitch/bending coupling. The choice of precone is determined primarily by the steady blade loads; fortunately the ideal value also results in the best flight dynamics.

Aft sweep of the blade outboard of the pitch bearing improves the hover and forward flight longitudinal oscillations, but degrades the lateral oscillation (figure 13). Similar results are given in reference 5 (figure 11). A lag instability is predicted for about 4° forward sweep, and a torsion instability at about 4° aft sweep. Blade droop outboard of the pitch bearing was found to have very little effect on the calculated flight dynamics. A lag instability is predicted for large down droop (at about 3.25° with a precone of 2.5°).

A forward shift of the blade center of gravity position relative to the pitch axis (figure 14), or an aft shift of the aerodynamic center (figure 15), improves the longitudinal oscillation in hover and forward flight, although there is some degradation of the lateral oscillation and vertical damping. Similar results are given in reference 6 (figures 16, 17, and 21). Figures 14 and 15 are nearly identical, demonstrating that

the relevant parameter is actually the chordwise offset between the center of gravity and aerodynamic center ($x_I - x_A$). Note that the longitudinal oscillatory mode in forward flight (100 knots) becomes two real roots at about $(x_I - x_A)/c = 0.03$, one of which is very unstable. A torsion instability is predicted for about $x_I - x_A = 0.04c$. Reference 7 describes the pitch and roll rate feedback resulting from a center of gravity/aerodynamic center offset with a torsionally soft blade, which produces the observed changes in the flight dynamics. Figure 16 shows the hover vertical mode time to half-amplitude variation with $x_I - x_A$. Offset of the center of gravity forward of the aerodynamic center (and also forward sweep of the blade) reduces $t_{\frac{1}{2}}$ by the following mechanism. An upward velocity of the helicopter produces a nose down pitch of the blades due to their inertial reaction. This blade pitch change reduces the rotor thrust. So there is a force produced opposing the helicopter motion, which implies increased damping.

None of these parameters was found to influence significantly the hover yaw root or the forward flight lateral oscillation, which are determined primarily by the tail rotor.

CONCLUDING REMARKS

The calculated dynamic characteristics of a representative soft-inplane hingeless rotor helicopter have been examined, including the flight dynamics and air resonance behavior; the analytical model required to accurately represent the dynamics of this helicopter; and the influence of the horizontal tail size and various rotor parameters on the flight dynamics and aeroelastic stability. The calculations show no evidence of an air resonance problem with this aircraft. The rotorcraft aeroelastic analysis developed in reference 1 proved to be a useful tool for this investigation.

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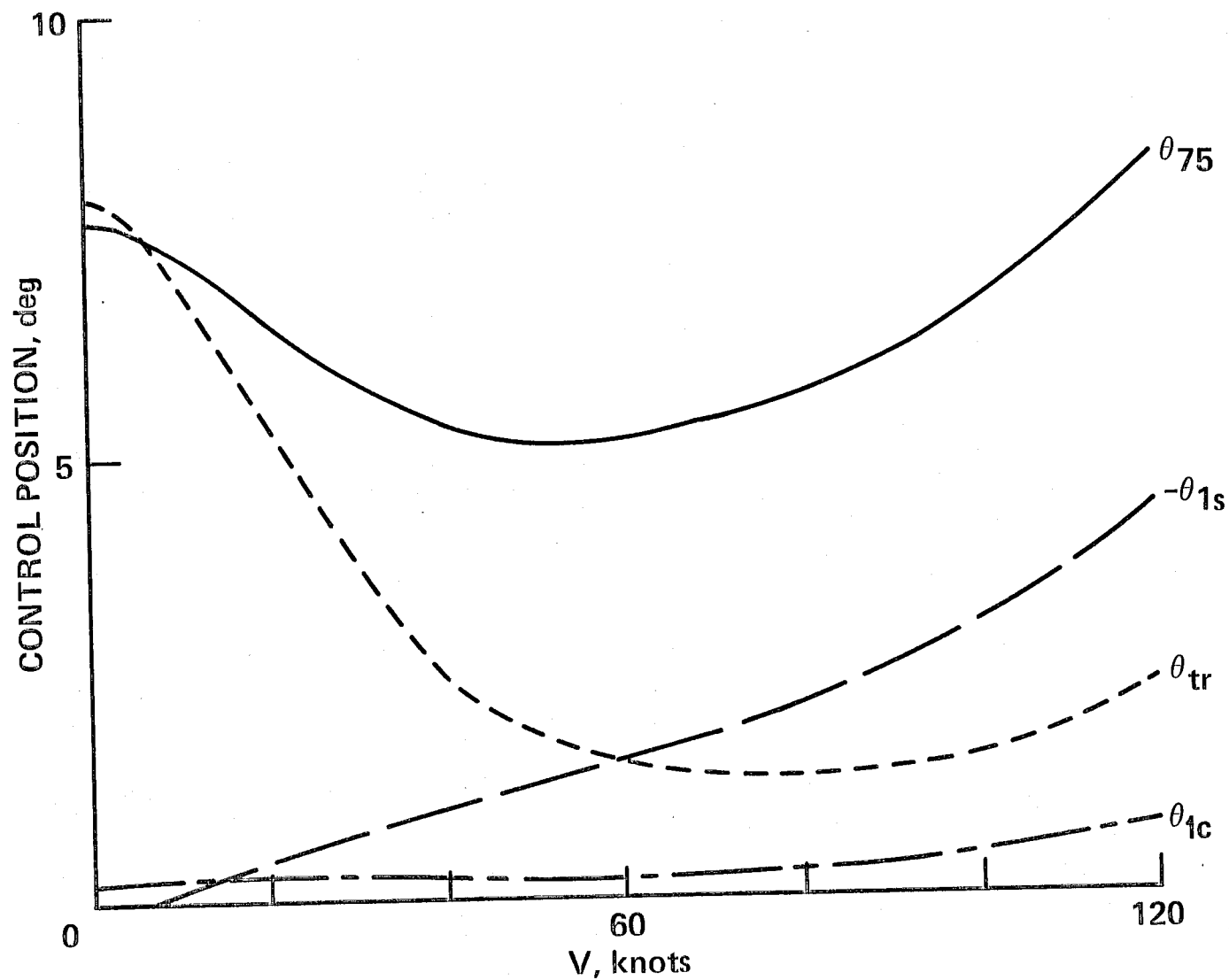


Figure 1 BC-105 helicopter trim: main rotor and tail rotor control angles.

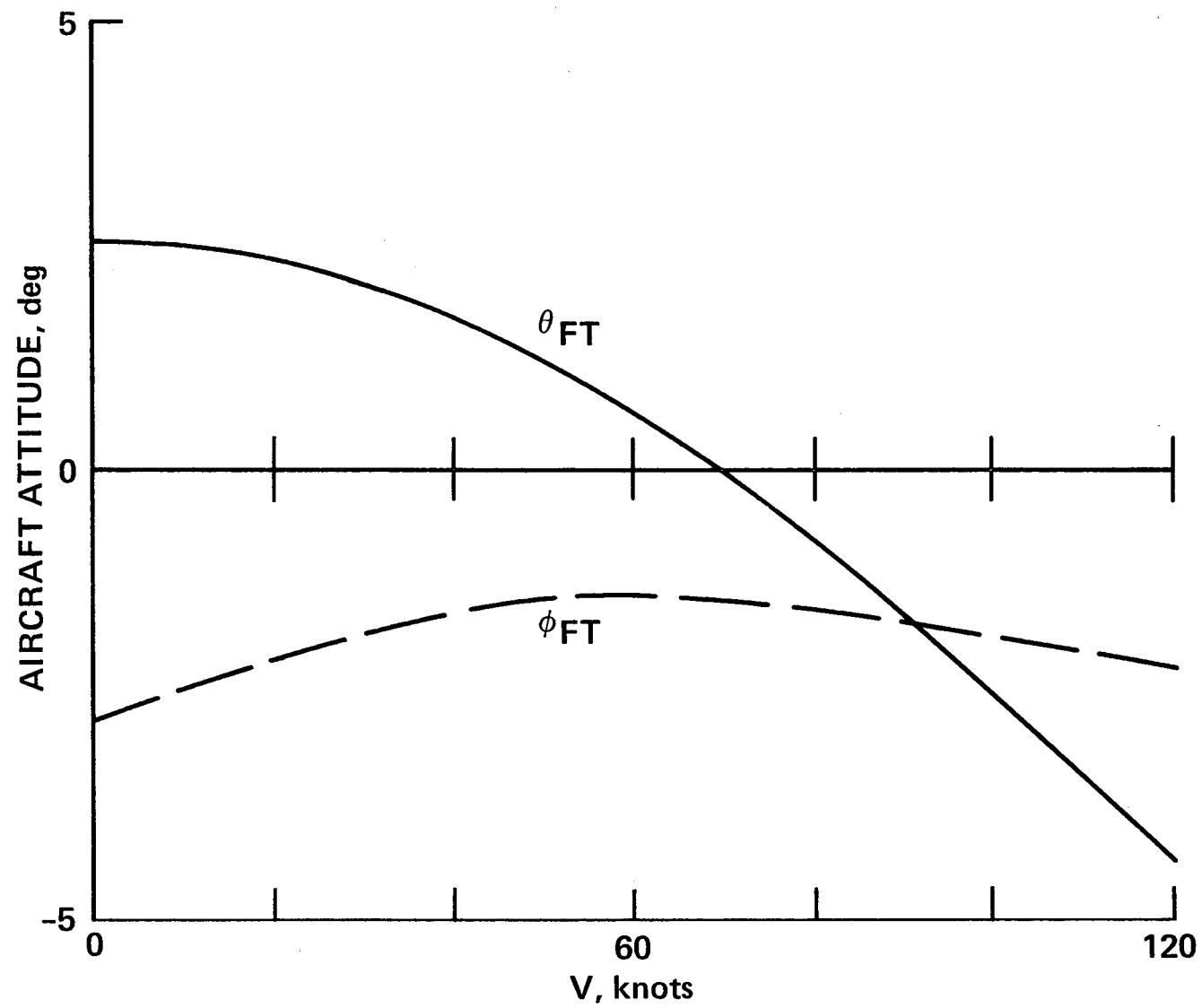


Figure 2 BO-105 helicopter trim: fuselage pitch and roll attitude.

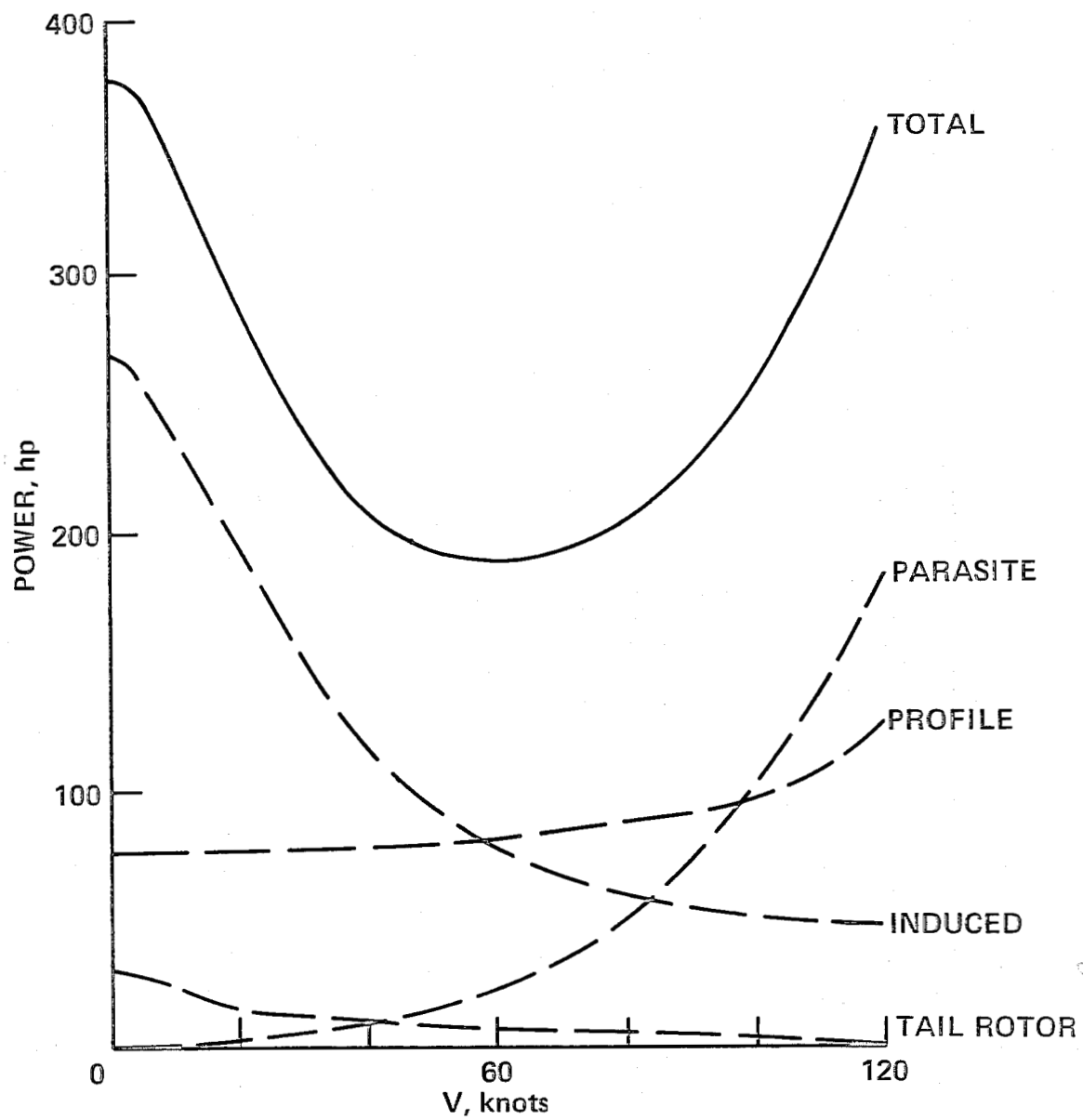


Figure 3 BO-105 helicopter trim: power required.

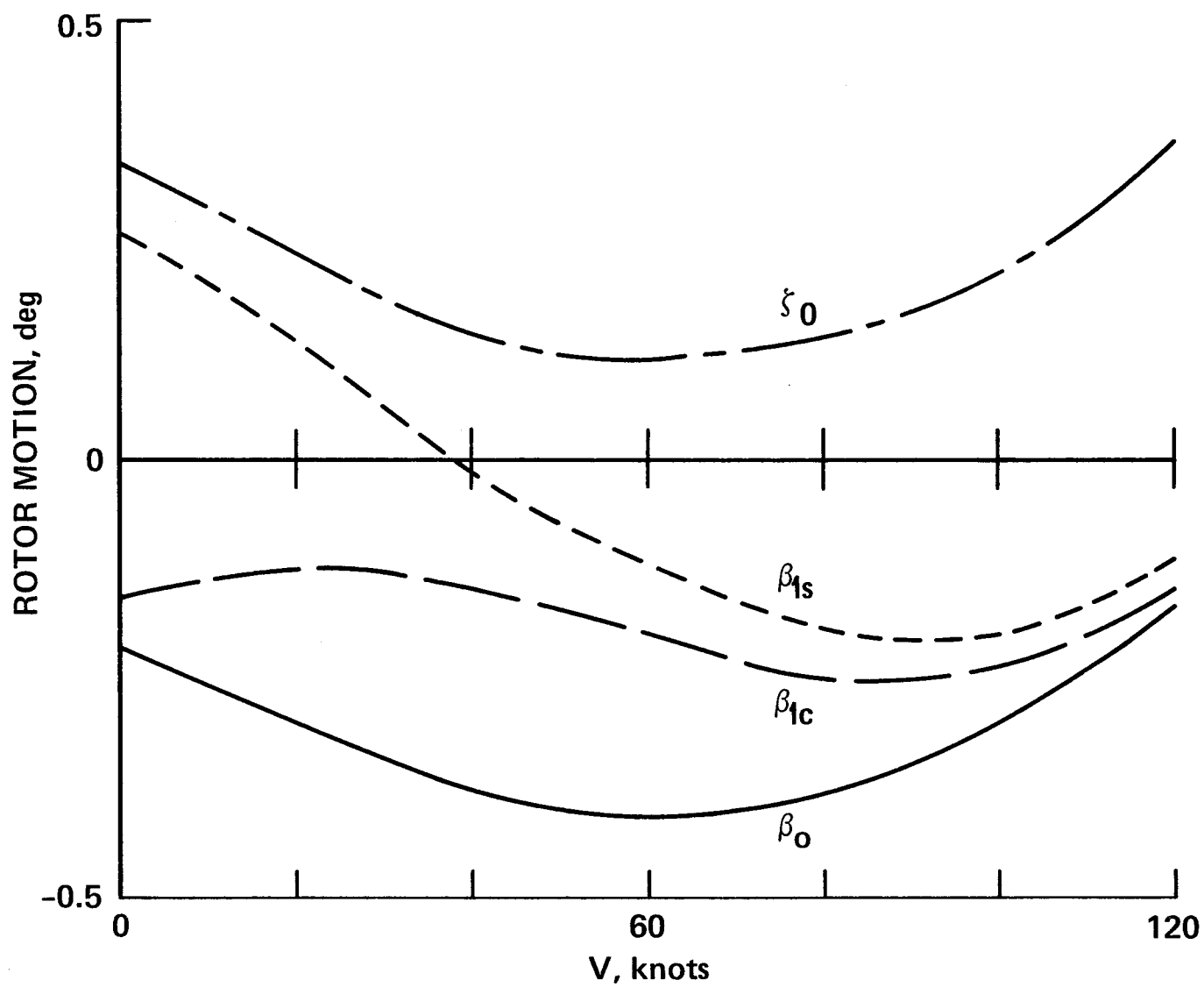


Figure 4 BO-105 helicopter trim: rotor flap and lag motion.

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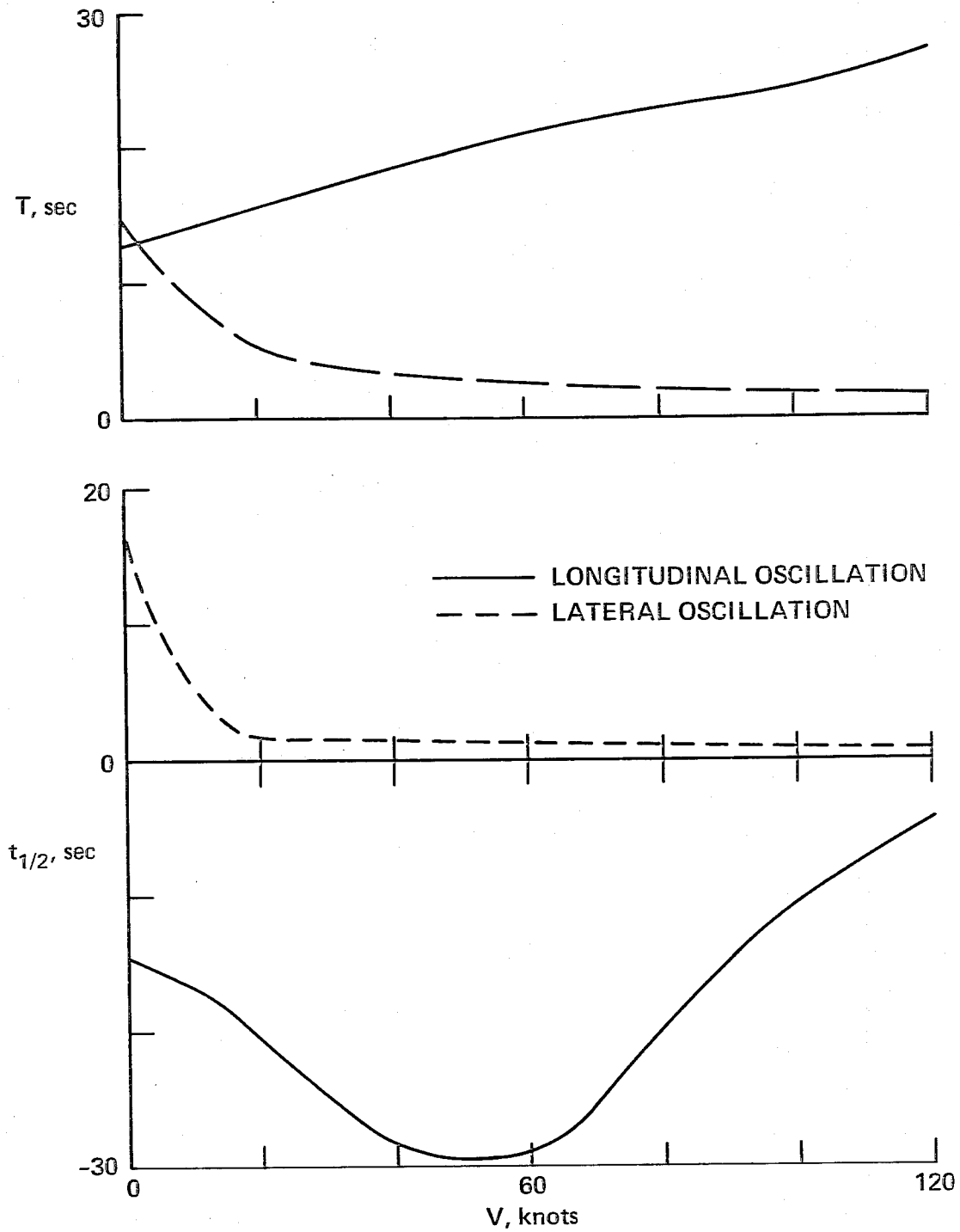


Figure 5 BO-105 helicopter flight dynamics: longitudinal and lateral oscillatory mode period and time to half-amplitude.

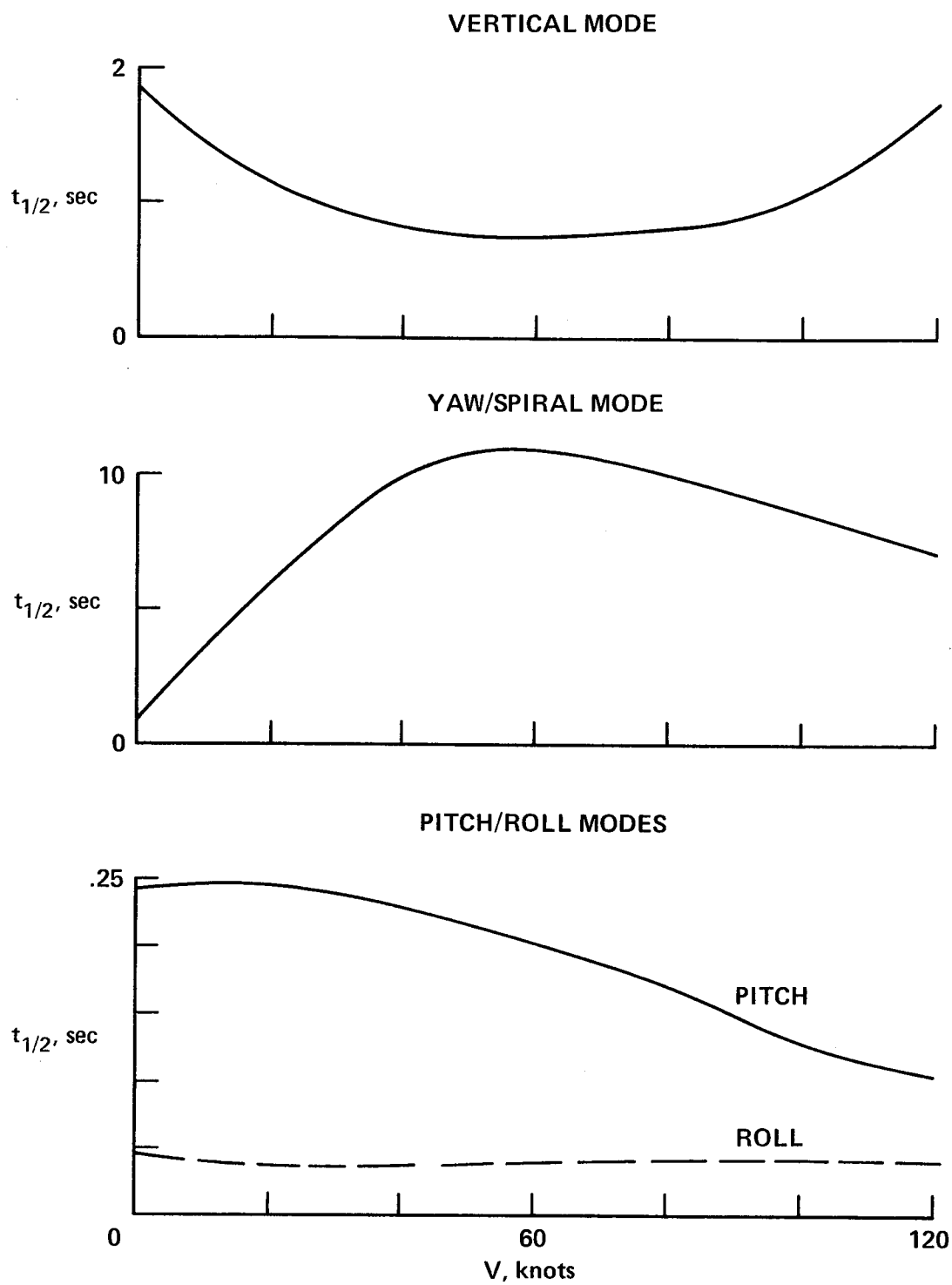


Figure 6 BO-105 helicopter flight dynamics: vertical mode, yaw/spiral mode, pitch mode, and roll mode time to half-amplitude.

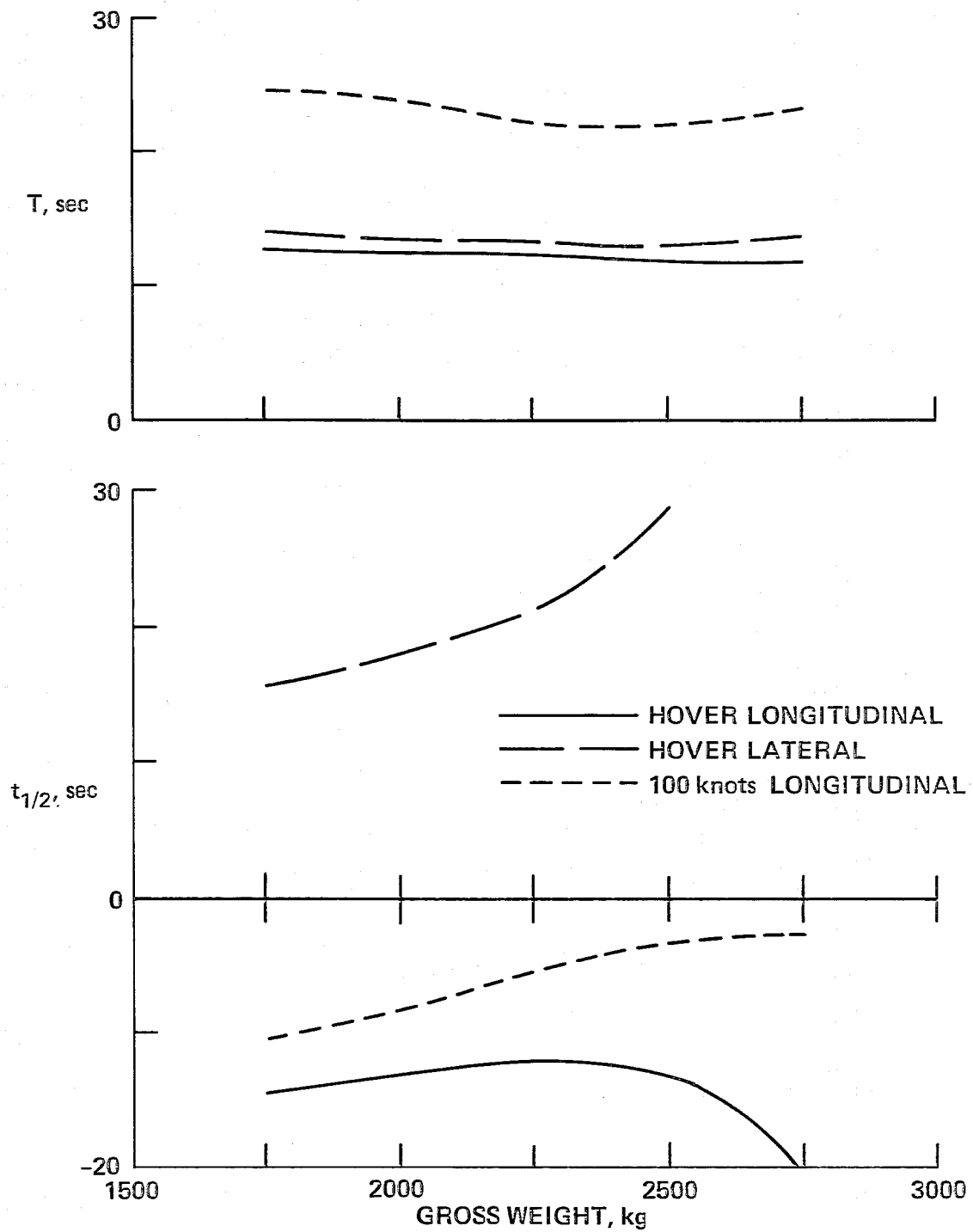
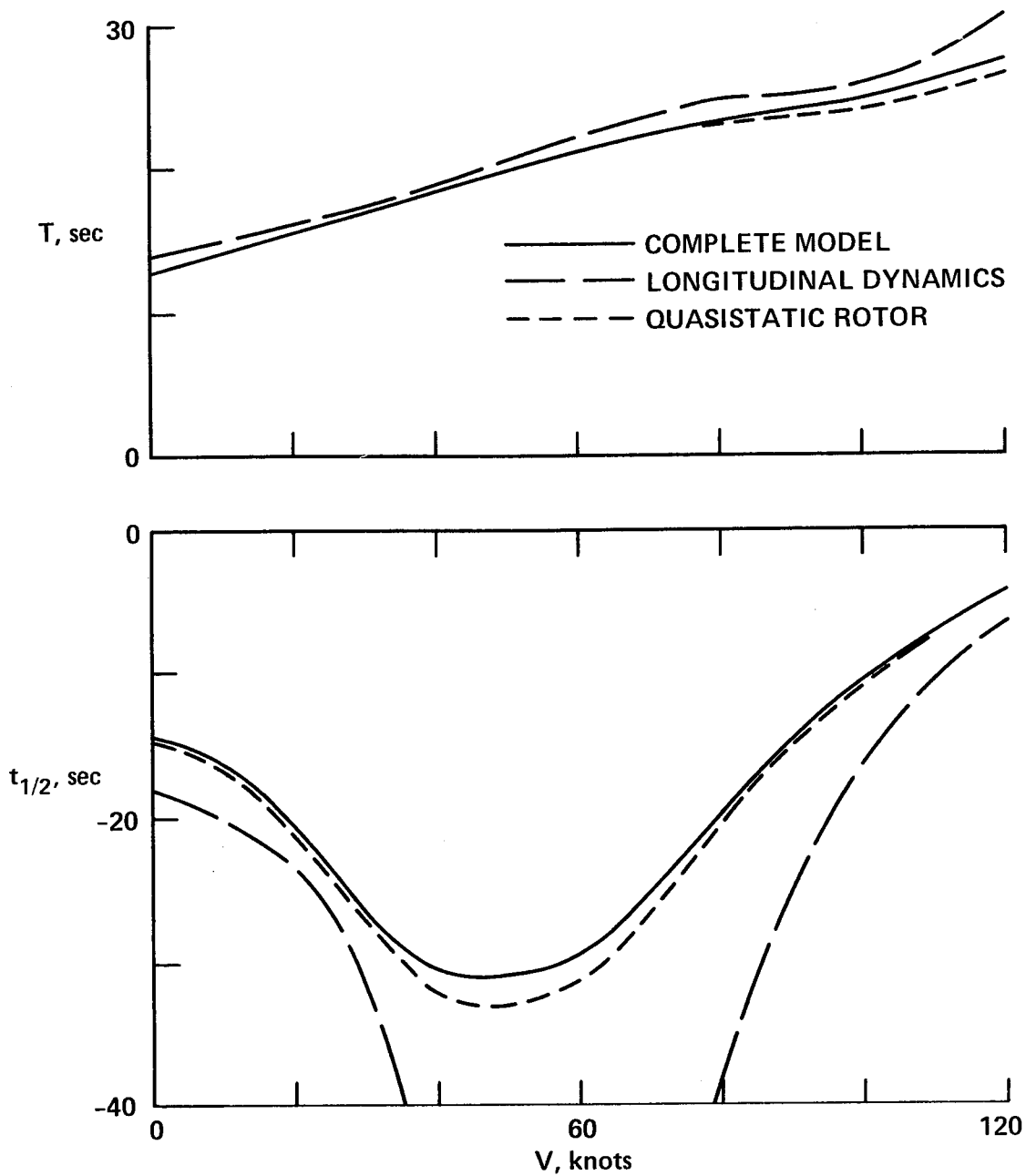
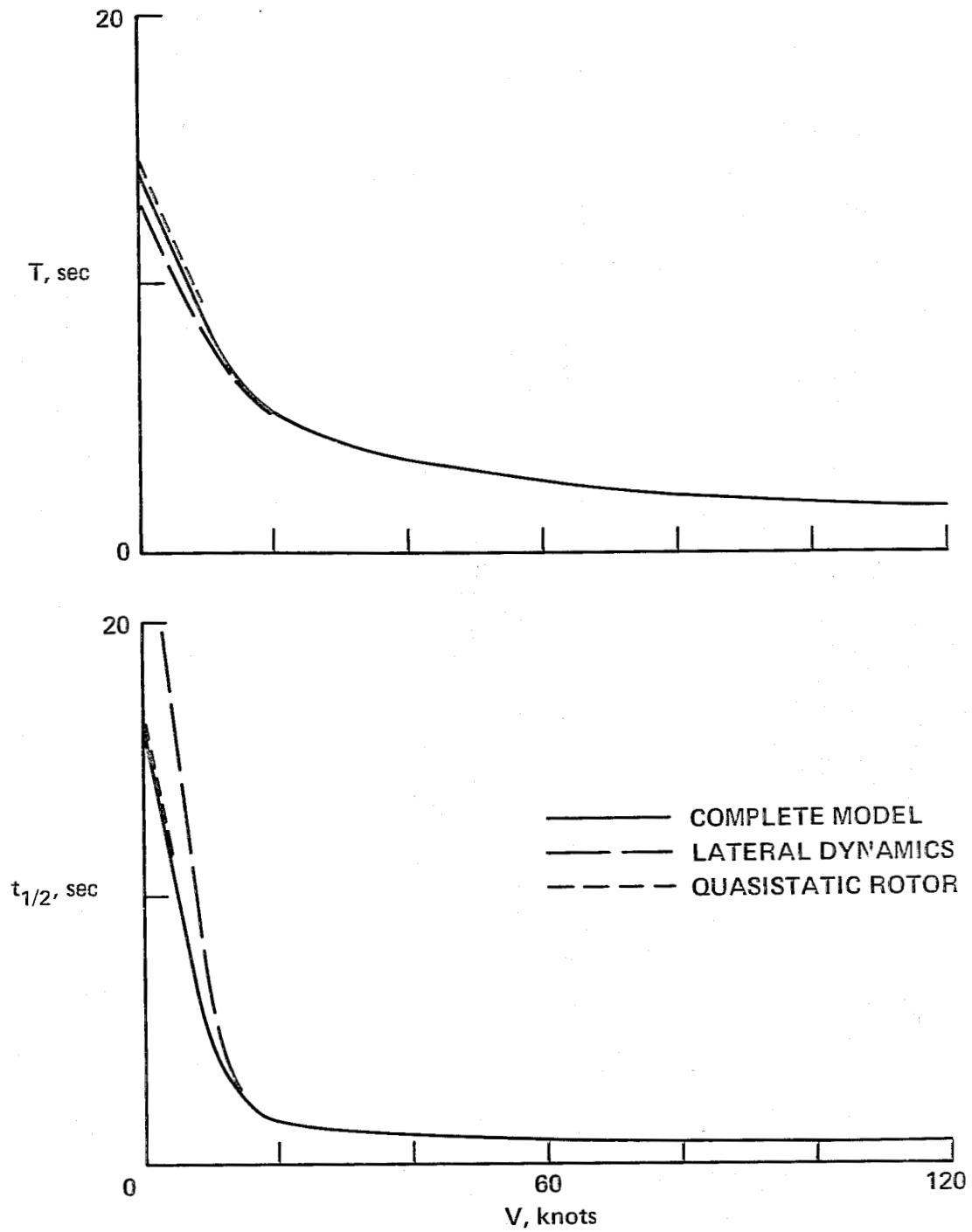


Figure 7 BO-105 helicopter flight dynamics: influence of gross weight on oscillatory modes in hover and at 100 knots.



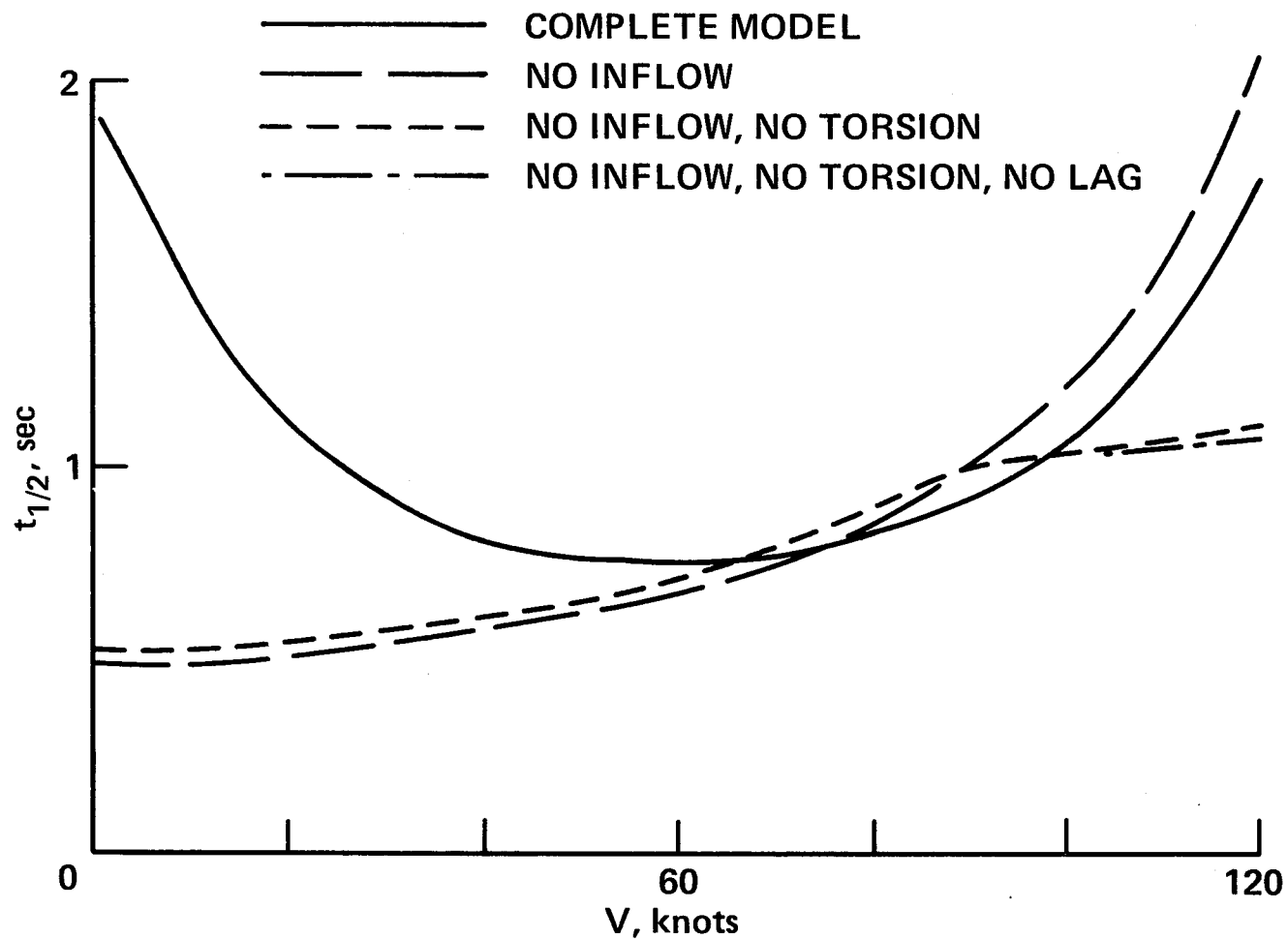
(a) Longitudinal oscillatory mode.

Figure 8 Analytical modelling requirements: influence of decoupled dynamics and quasistatic rotor approximations on the calculated flight dynamics.



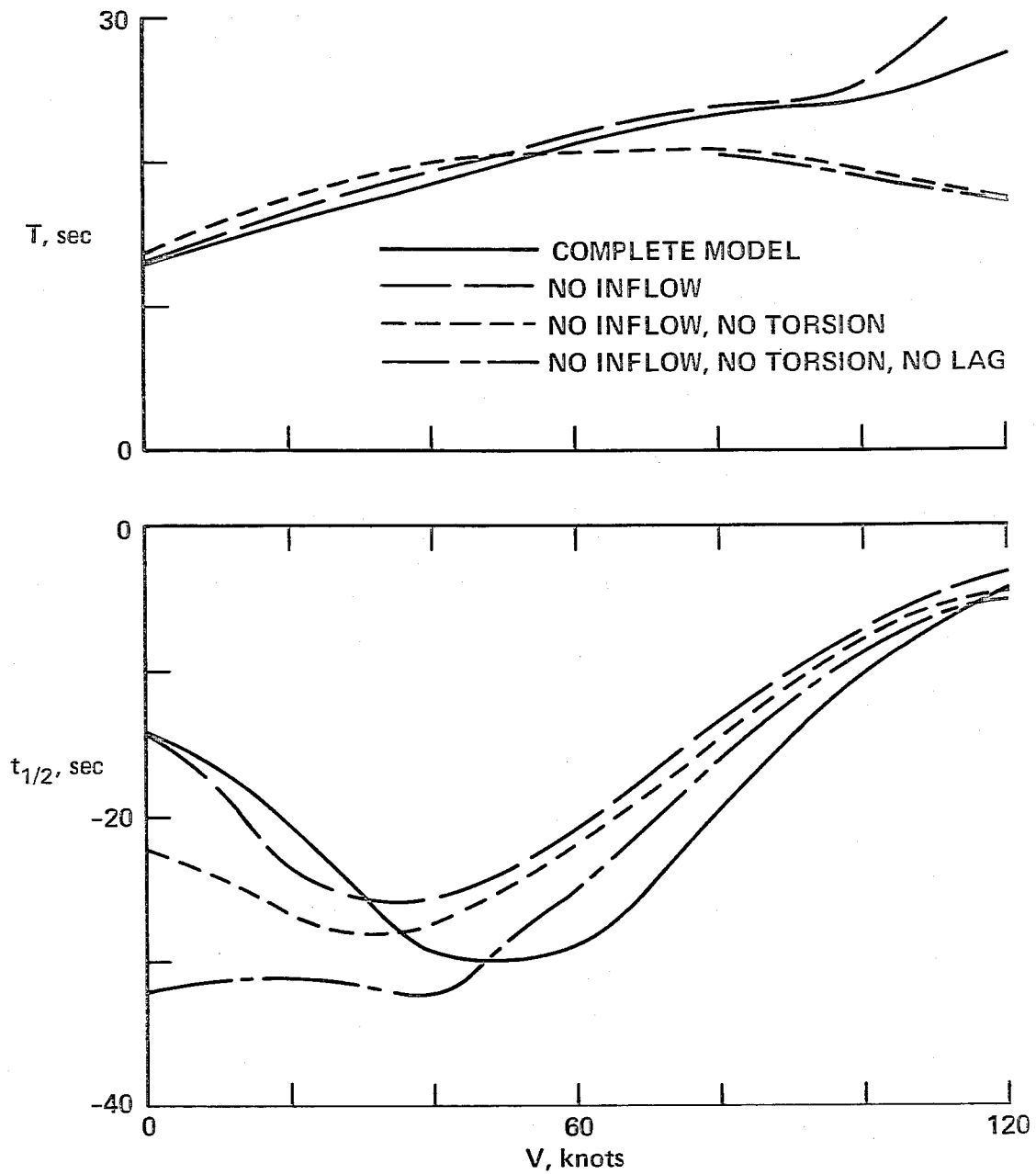
(b) Lateral oscillatory mode.

Figure 8 Concluded.



(a) Vertical mode.

Figure 9 Analytical modelling requirements: influence of the rotor inflow perturbation, blade torsion motion, and blade lag motion on the calculated flight dynamics.



(b) Longitudinal oscillatory mode.

Figure 9 Concluded.

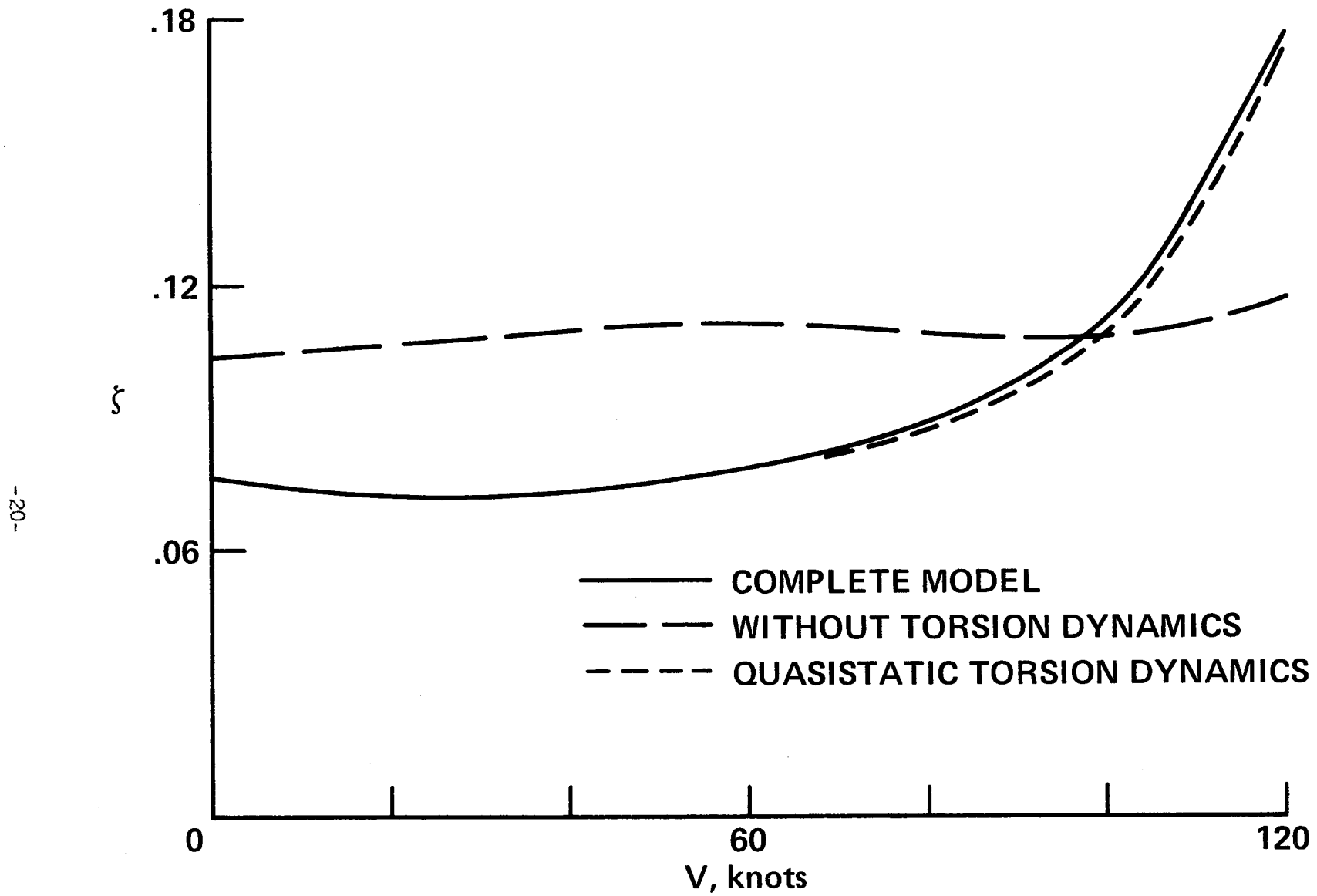


Figure 10 BO-105 helicopter air resonance: damping ratio of the low frequency lag mode.

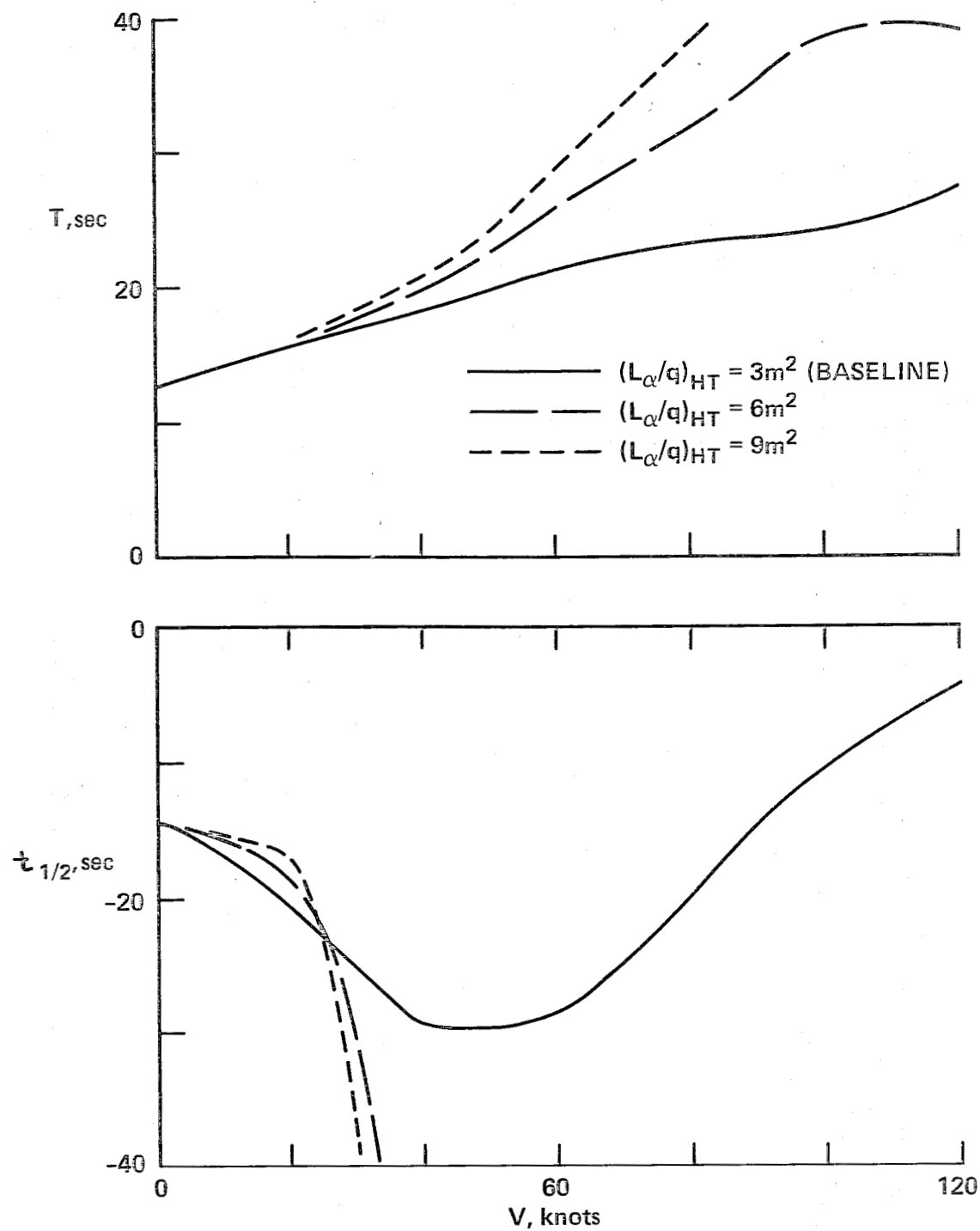


Figure 11 BC-105 helicopter calculated flight dynamics: influence of horizontal tail size on the longitudinal oscillatory mode.

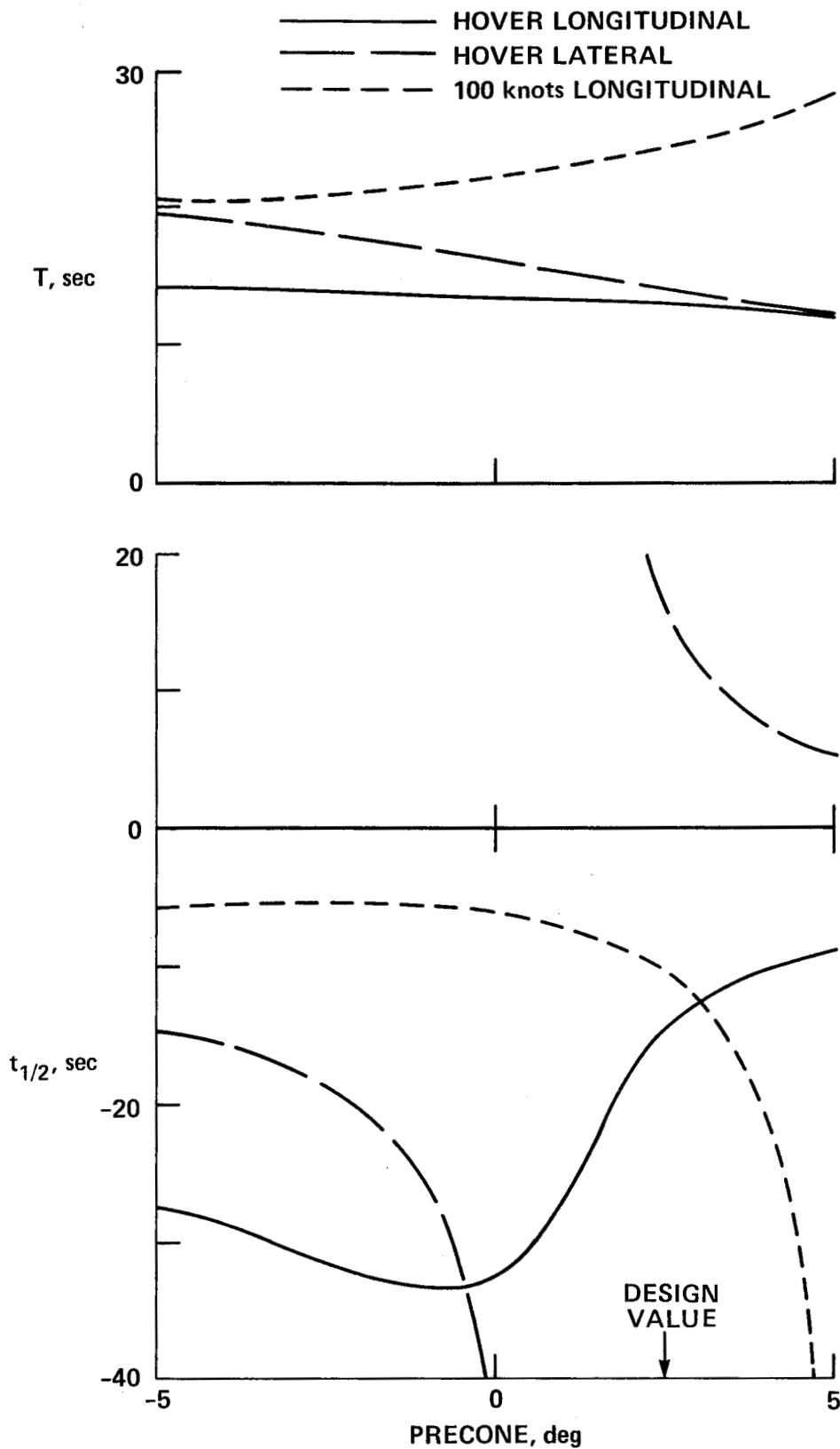


Figure 12 BO-105 helicopter calculated flight dynamics: influence of hub precon angle on the oscillatory modes.

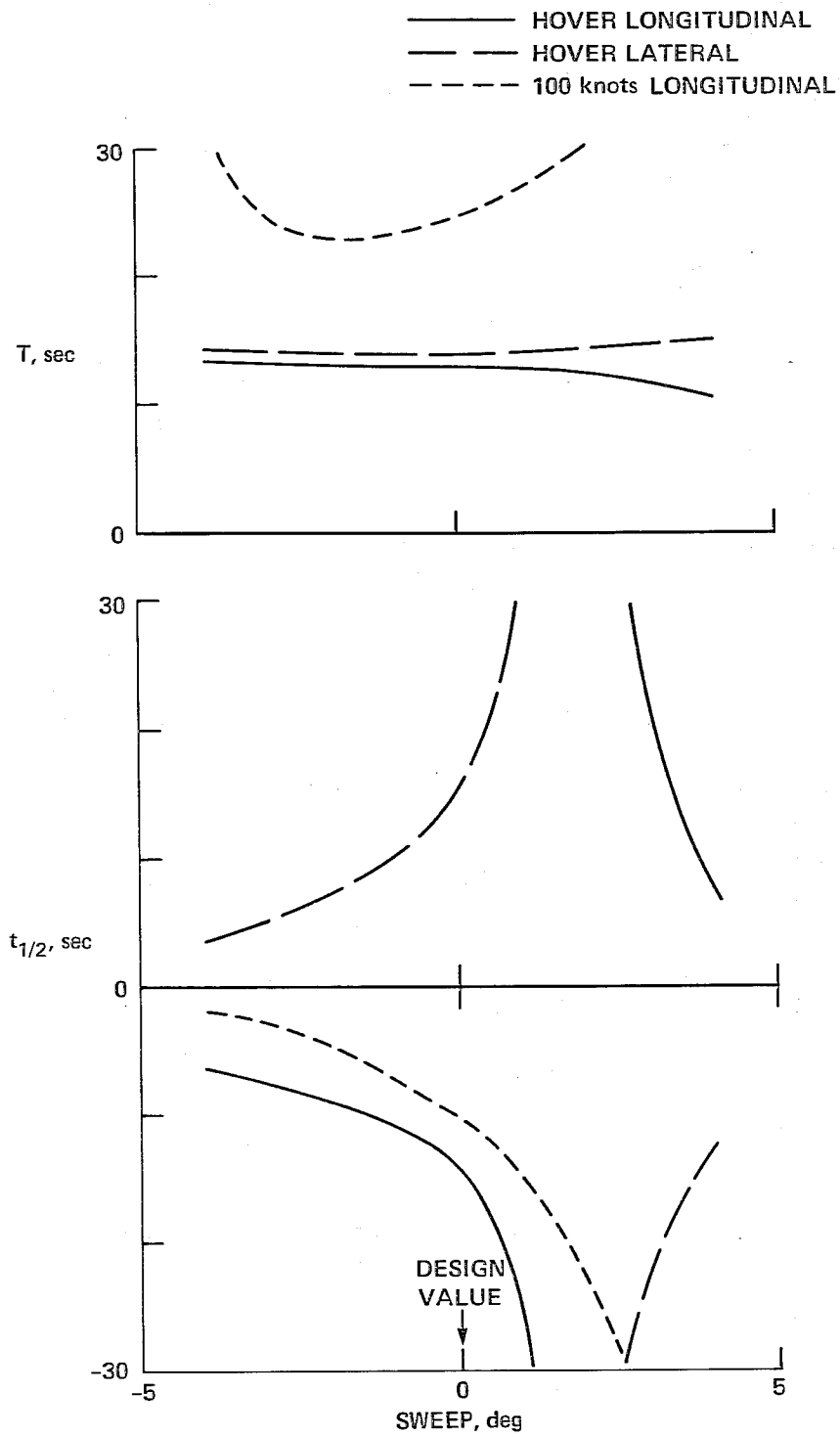


Figure 13 BO-105 helicopter flight dynamics: influence of the blade sweep (positive aft) on the oscillatory modes.

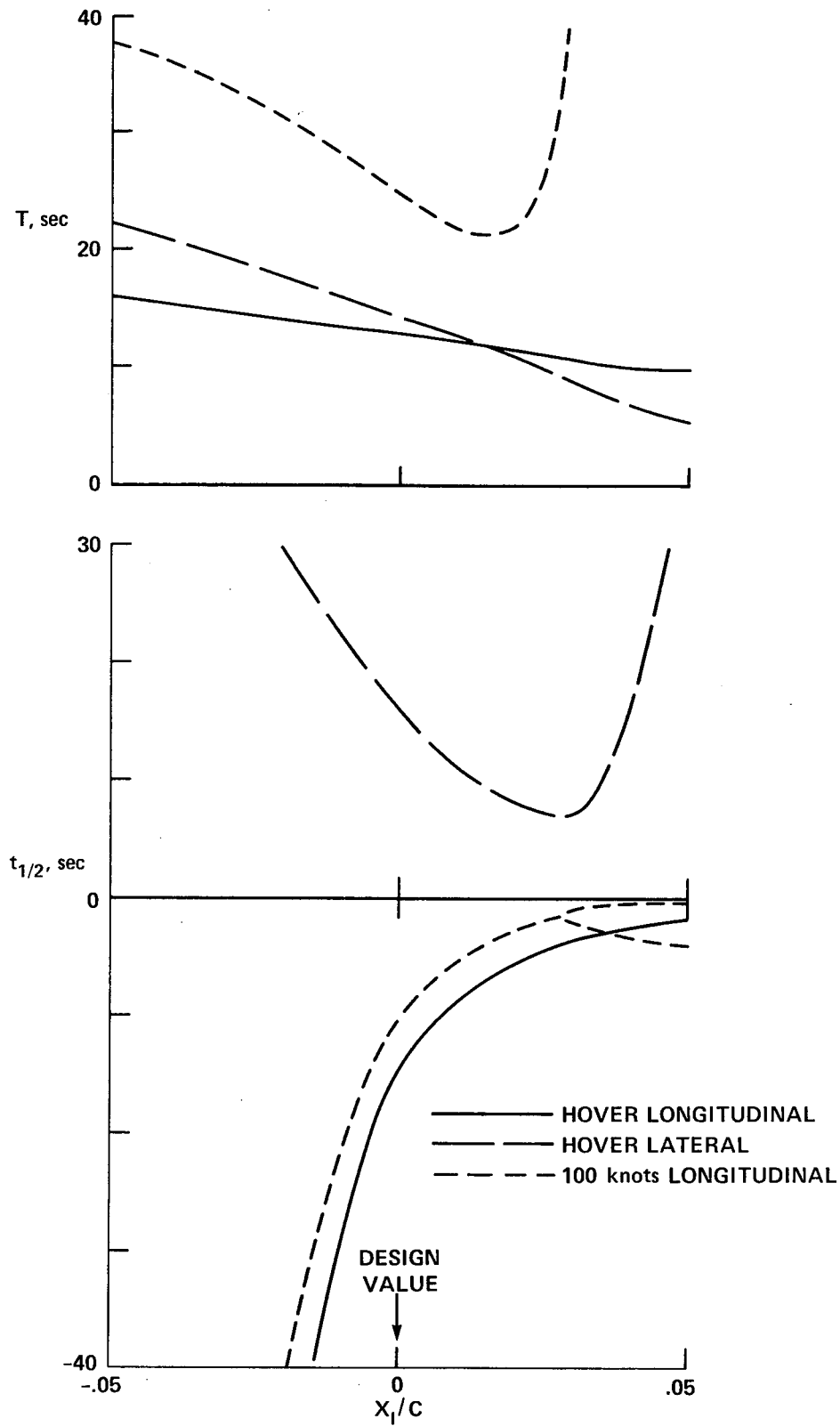


Figure 14 BO-105 helicopter calculated flight dynamics: influence of the blade chordwise center of gravity position (x_I positive aft of the pitch axis) on the oscillatory modes.

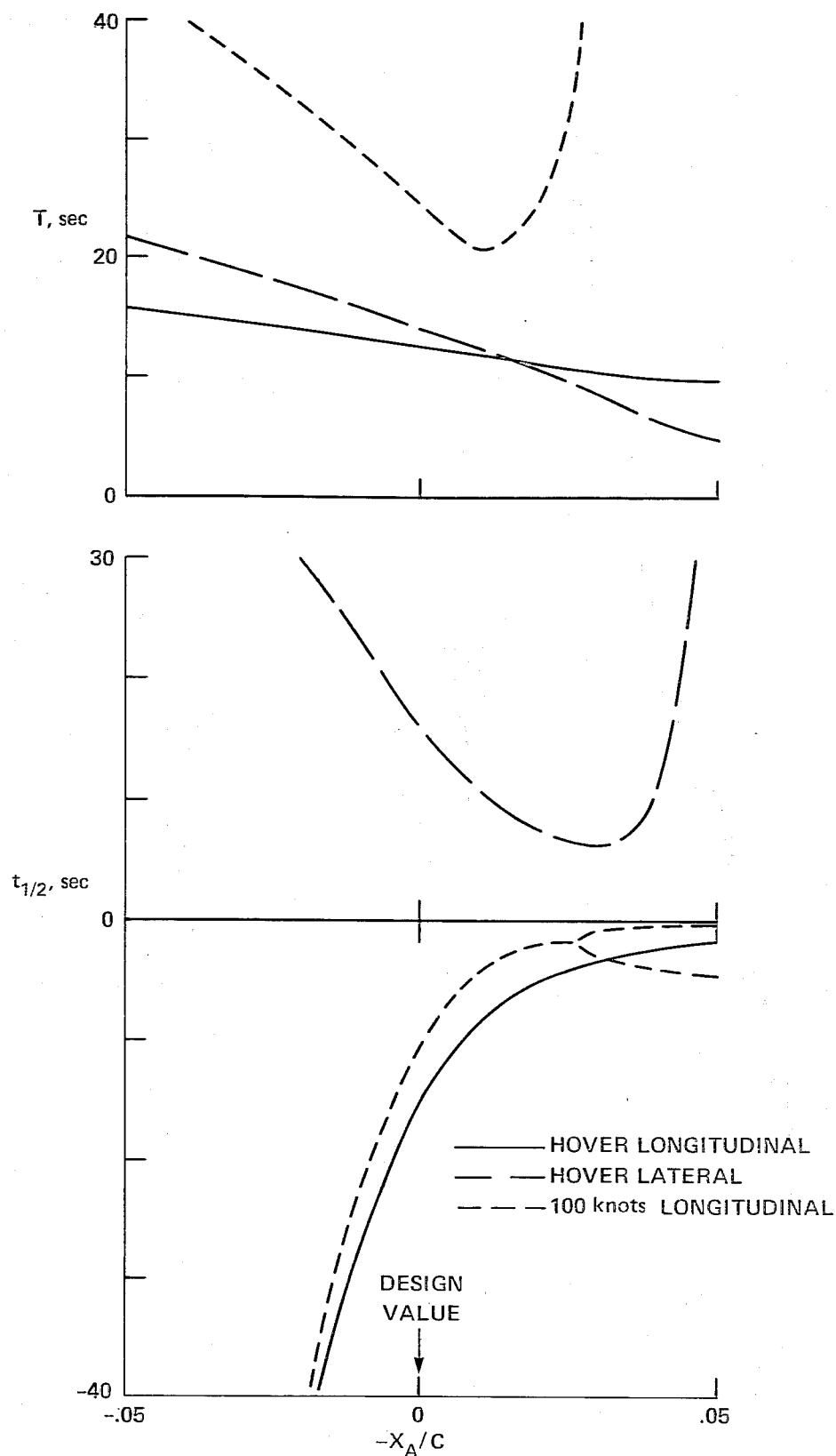


Figure 15 BO-105 helicopter calculated flight dynamics: influence of the blade chordwise aerodynamic center position ($-x_A$ positive forward of the pitch axis) on the oscillatory modes.

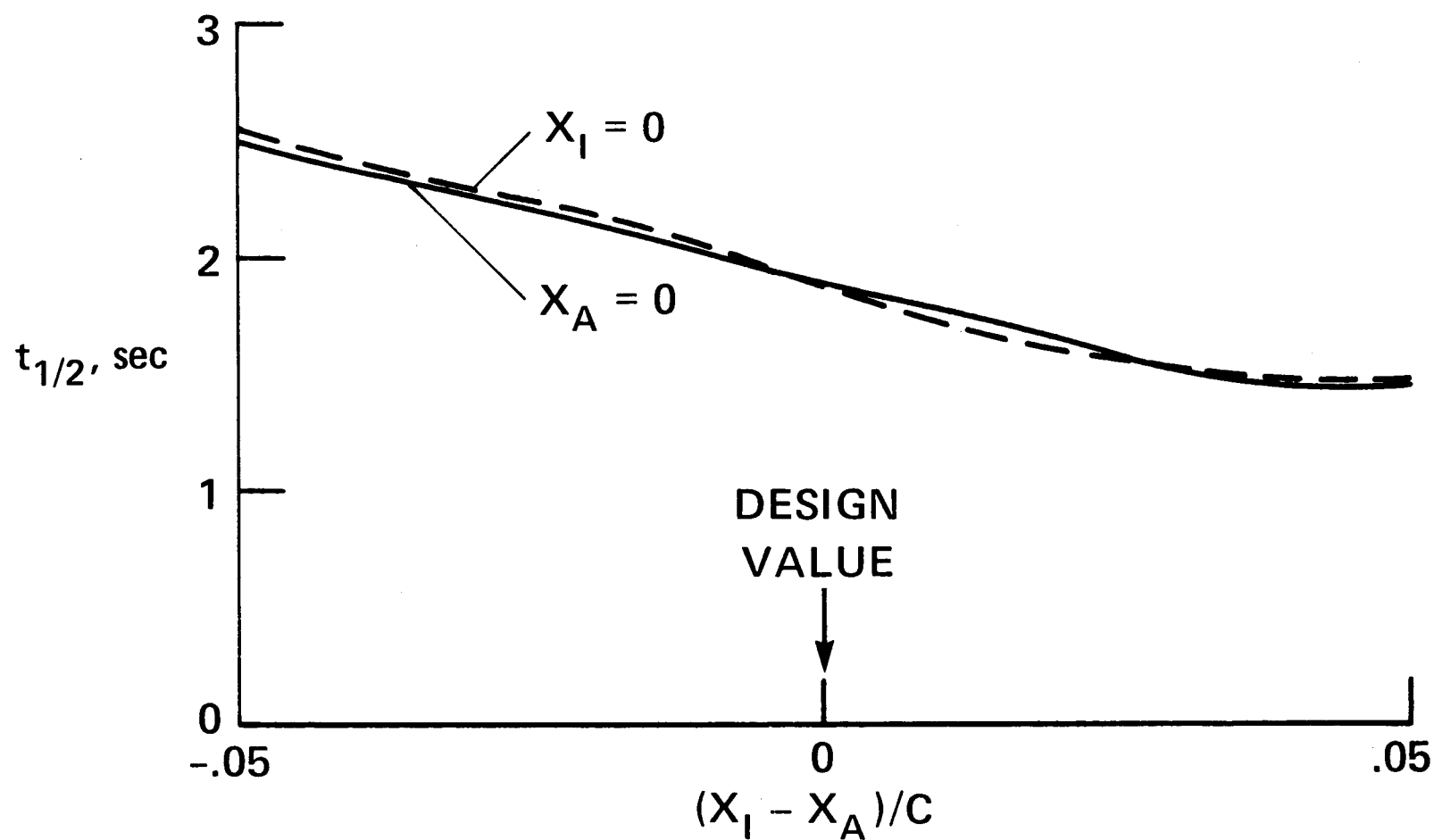


Figure 16 BO-105 helicopter calculated flight dynamics: influence of the blade chordwise center of gravity/aerodynamic center offset ($x_I - x_A$ positive for the CG aft of the AC) on the hover vertical mode.

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